DEPARTMENT OF THE INTERIOR

CANADA

HON. W. J. ROCHE, *Minister*. W. W. CORY, C.M.G., *Deputy Minister*.

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EXPERIMENTS ON METHODS FOR INCREASING THE EFFICIENCY OF SPECTROGRAPHS IN RADIAL VELOCITY DETERMINATIONS.

BY J. S. PLASKETT, B.A., D.SC., F.R.S.C.

INTRODUCTION.

It is a well known fact and has been repeatedly stated that the modern star spectrograph is exceedingly wasteful of light. If we leave out of consideration for the present the light occulted by the slit jaws, careful computation of the losses by absorption and reflection in the optical train shows that at H_γ about 25 per cent. of the light is transmitted by a one-prism and about 8 per cent. by a three-prism spectrograph. The loss at the slit will depend upon its width, the focal length of the telescope objective and the conditions of "seeing" and will vary from 50 to 90 per cent. If we add losses in the objective of the telescope, we get from 2 to 8 per cent. of the incident star light in a one-prism and from 0.6 to 3 per cent. in a three-prism spectrograph effective in producing the spectrum.

This was recognized at the meeting of the Committee of the Astronomical and Astrophysical Society of America on Co-operation in Radial Velocity Determinations at Mt. Wilson in 1910, and methods of increasing the efficiency of the spectrograph were discussed and various suggestions offered. As the writer's part of the work, and with the consent of the Director, Dr. King, experiments on the use of the plane grating as the dispersion piece of a stellar spectrograph were undertaken, and the results are recounted in the first part of this publication.

A discussion with Dr. Frank Schlesinger, Director of the Allegheny Observatory, at the Astronomical and Astrophysical Society meeting at Pittsburg in August 1912 resulted in the experiments on the length of spectrum detailed in the second part. The marked gain in intensity, at the violet, of the spectra produced by the grating and by objective prisms of light flint as compared with those obtained by the dense flint prism of the Ottawa Spectrograph led to the test of new optical parts of less absorbing glass for this instrument.

I. THE PLANE GRATING AND HALF-PRISM FOR STELLAR SPECTROSCOPY.

Experiments on the use of gratings for the production of stellar spectra have been made by Poor and Mitchell,[1] by Wadsworth[2] and by others but without very encouraging results. The difficulty was probably due to the loss of light entailed by its distribution over several spectra and can be overcome by a grating giving a strong concentration of light in one order. Gratings have been ruled by Rowland giving a very strong first order spectrum, and both Michelson and Ames considered it possible to rule gratings giving as much as 75 per cent. of the intensity in one spectrum. Even if this efficiency is not reached, grating spectra should compare favourably with those produced by three-prism dispersion especially toward the violet, where the dense flint glass used in most prism trains is strongly absorbing.

A plane grating, to give the most intense possible first order spectrum at one side, was ordered through the John A. Brashear Company, in October 1910, was ruled by Dr. J. A. Anderson of Johns Hopkins University and received in January, 1912. The grating is a 5-inch plane with ruled surface $7 \cdot 4 \times 9 \cdot 4$ cm ($2 \cdot 87 \times 3 \cdot 75$ inches), ruling 15000 to the inch. The total number of lines is 55875, which will be the resolving power in the first order if the whole aperture is used. Dr. Anderson estimated that about 50 per cent. of the light was concentrated in one first order, but a misunderstanding by the writer led him to think this was the percentage

[1] Astrophysical Journal, 7.157, 1898.
[2] Ibid 7, 198, 1898.

of the incident light, whereas it referred to the light returned from the speculum metal surface. As the reflectivity of speculum metal is about 65 per cent., it is evident that we have only about 33 per cent. of the light in the one order.

Considerable thought was given to the optical design of the spectrograph, and three methods of producing a spectrum were combined in the one instrument. In the first of these, a parallel pencil from a doublet collimator objective of 57 mm (2·25 in.) aperture is diffracted back, making an angle of about 30° with the initial direction, the spectrum being formed by a triplet camera objective of 63·4 mm (2·5 in.) aperture and 507 mm (20 in.) focus. In the second method the autocollimating or Littrow principle is used, the combined collimator and camera objective being a triplet of 63·4 mm (2·5 in.) aperture and 951 mm (37·5 in.) focus. The spectrum is formed in the plane of, and as close as possible to, one end of the slit. The same principle is used in the third method, the grating being replaced by a half-prism of O 102 glass having angles of 31°·5, 58°·5, and 90°, and silvered on the side opposite the 58°·5 angle. The light is refracted into the prism on the hypotenuse and, when at minimum deviation, is incident normally on the silvered side and returned along its original path, except for the slight inclination necessary to bring it on the plate. The use of the half-prism for radial velocity work was proposed by Professor Campbell at the meeting above referred to, and I understand a stellar spectrograph has been constructed at the Lick Observatory from his designs which gives very promising results. Nevertheless, as no change was needed in the grating spectrograph except the substitution of the half-prism for the grating, it was thought worth while to make tests of this type.

The linear dispersions of the three forms are 33·0Å, 17·5Å, and 17·5Å per millimetre at $H\gamma$. These values are almost identical with those given by spectrograph I (33·4Å) and spectrograph III S (17·5Å), one- and three-prism spectrographs of the Dominion Observatory, thus enabling accurate comparisons of relative intensities to be easily made.

The mechanical design of the spectrograph follows the supported box form, first introduced by Campbell at the Lick Observatory, of which successful examples besides those at Mount Hamilton and in Chile are the Mellon spectrograph at Allegheny and the single-prism spectrographs at Ottawa and Ann Arbor. The box is made of brass plates firmly screwed together at the angles and thoroughly braced internally. Owing to its relative compactness as compared with the Ottawa one-prism, it was not thought necessary to introduce a third counterbalancing support as in the latter instrument, but the box is held flexibly and yet firmly in the braced T-iron frame by two supports so placed as to reduce flexure to a minimum. The objectives, which define beautifully, and the reflecting slit were made by the J. A. Brashear Company, but all other parts of the instrument were constructed in the observatory workshop. The form of the instrument, the position of the plate-holders in the regular and Littrow forms and its method of attachment to the frame and telescope are well shown in Plate I.

The spectrograph was set up and thoroughly tested and adjusted in the laboratory before using it in stellar work. The source of light employed was the carbon arc, which is not only easily produced, but which gives a large number of well distributed lines and flutings, and only requires very short exposures. It was expected that some difficulty would be encountered in the Littrow form from the light reflected from the lens surfaces fogging the plate. Fortunately the effect, if present, was quite inappreciable, and it was not found necessary, as in the solar spectrograph, to use an occulting bar or tilt the lens. The definition was found to be slightly superior when the axis of the objective passed through the centre of the plate rather than through the centre of the slit, the angle between the two being less than a degree. The field is practically flat over the range of spectrum included on the plate, and the definition excellent with both grating and half-prism.

The method adopted for obtaining the comparative intensities of prismatic spectra was to make exposures successively on the same celestial objects, both sun and stars being used. Five spectra, side by side on the same plate, were made of the object by each instrument, the exposure times in every case being proportional to the numbers 1, 1·5, 2, 3, 4. For example, on

Procyon, 5 exposures were made with III S, 5 with the Littrow grating, 5 with the Littrow half-prism, and then 5 with III S, all three instruments having the same dispersion. A similar test was carried through with the first form of the grating spectrograph and the one-prism instrument, both of the same dispersion, and repeated for other stars and for the sun. As the linear dispersions were the same, the spectra of the same width, the observing conditions fairly constant, the exposure times the same, and the plates developed together for the same time, the intensity of the resulting negatives gives a direct comparison of the intensity of the spectra. As nearly equal intensities on the plates can be compared, little photographic error is likely to occur. The results of these comparisons are given in the subjoined table.

RELATIVE INTENSITIES OF SPECTRA.

Wave-Length.	Sun.			Procyon.				Rigel.				Mean (Stars).			
	G.	3 P.	½ P.	G.	3 P.	½ P.	1 P.	G.	3 P.	½ P.	1P.	G.	3 P.	½ P.	1 P.
H	.....	2·0	3·0	0·6	2·0	4·0	5·0	0·7	2·0	3·5	5·0	0·7	2·0	3·7	5·0
4800	0·9	3·2	4·0	1·0	3·0	5·5	6·5	1·0	5·0	5·0	6·0	1·0	4·0	5·2	6·2
4700	1·3	4·5	4·5	1·3	2·5	5·5	6·5	1·2	4·2	5·0	6·0	1·2	3·3	5·3	6·3
4600	1·5	5·2	4·5	1·3	2·0	5·0	6·0	1·2	3·0	5·0	5·6	1·3	2·5	5·0	5·8
4500	1·3	4·5	4·0	1·2	1·8	4·0	5·0	1·2	1·9	3·8	5·0	1·2	1·8	3·9	5·0
4400	1·1	3·0	3·5	1·1	1·4	3·0	3·9	1·1	1·5	2·8	4·3	1·1	1·5	2·9	4·1
H	1·0	2·3	3·0	1·0	1·3	2·5	3·3	1·0	1·4	2·3	3·5	1·0	1·3	2·4	3·4
4300	1·0	2·0	2·8	1·0	1·1	2·5	3·0	1·0	1·1	2·3	3·0	1·0	1·1	2·4	3·0
4200	1·1	1·2	2·6	1·0	0·7	2·3	2·5	1·0	0·8	2·0	2·4	1·0	0·8	2·2	2·5
4150	1·1	0·7	2·0	1·1	0·3	2·2	2·2	1·0	0·3	1·8	2·0	1·0	0·3	2·0	2·1
H	1·1	0·5	1·8	1·1	0·1	2·0	2·0	1·0	0·1	1·6	1·8	1·1	0·1	1·8	1·9
4050	1·0	0·2	1·6	1·1	.....	1·7	1·7	1·0	.....	1·4	1·5	1·0	.....	1·5	1·6
4000	1·0	.....	1·3	1·0	.....	1·4	1·3	1·0	.....	1·2	1·2	1·0	.....	1·3	1·3
H	1·0	.....	1·0	1·0	.....	1·0	1·0	1·0	.....	1·0	1·0	1·0	.....	1·0	1·0
K	0·9	.....	0·7	1·0	.....	0·8	1·8	1·0	.....	0·8	0·8	1·0	.....	0·8	0·8
3900	0·8	.....	0·2	0·9	.....	0·5	0·6	0·9	.....	0·4	0·4	0·9	.....	0·4	0·5
3850	0·3	.....	.....	0·6	.....	0·1	0·2	0·8	.....	0·2	0·2	0·7	.....	0·1	0·2
3800	.....	.....	.....	0·2	.....	.....	.....	0·6	.....	.....	.....	0·4	.....	.....	.....
3750	.....	.....	.....	.....	.....	.....	.....	0·3	.....	.....	.....	0·2	.....	.....	.....

The most striking feature in the appearance of the grating as compared with prismatic spectra, which is well shown in Plate II. as well as evident from the table, is the remarkable uniformity in intensity between Hβ and λ3850. This uniformity is perhaps the most useful property of the grating spectrograph. The contrast between grating and prism in this respect is very striking, as prismatic spectra are over ten times, grating spectra only

one and a third times, as intense at λ4700 as at λ3900. The difference is due in the main to two causes: first, the increased dispersion toward the violet and diminished toward the red of prismatic spectra (dispersion at K one and a half times, at H_β two-thirds, that at H_γ), while diffraction spectra are nearly normal; and second, the strong absorption of the prism glass for the shorter wave-lengths. Calculations from Vogel's constants for O 102 glass show that through 5 cm. of this glass, about the mean length of path through the single and the half-prism, 33 per cent. is transmitted at the K line as compared with 71 per cent. at H_γ and 85 per cent. at H_β. The effect of this absorption is strikingly shown in the table, where the relative intensity of three-prism as compared with single- and half-prism spectra toward the violet is given.

Discussing first the relative intensity of three-prism and grating spectra, we find the former has the advantage from H_β to about λ4300, while from λ4200 down grating spectra are decidedly superior, three-prism spectra disappearing below H_δ. If a spectrum in which the region from λ4300 to the ultra-violet is required, only the grating could be used, while from H_β to H_γ the prisms would have the advantage. In other words for early-type stars use the grating, for solar type, three-prism dispersion.

Comparing next, grating with single- and half-prism spectra we find the advantage lies decidedly with the latter above the H and K lines, but if the K line is required, as is the case in many early-type stars, it can be obtained with the grating in the same time as with the one-prism spectrograph without making the lines between H_β and H_γ immeasurable by over-exposure.

If now the prismatic spectra are intercompared, the superiority of one- over three-prism is markedly shown. The former gives nearly three times the intensity above λ4200 and a much greater ratio below, a difference of more than a magnitude in the stars within reach of the telescope. It must not be forgotten, however, that this difference is partially offset by the

threefold greater resolving power of three prisms, although in photographic spectra their high resolution cannot be effectively employed, and it is of no value in early-type stars.

A final interesting comparison is that between the one-prism and the half-prism spectra. The former gives spectra about 20 per cent. more intense than the latter, a result to be expected when the loss at the silvered reflecting surface is taken into account and when the larger aperture of the half-prism (63·4 mm. as compared with 51 mm.) and the consequent greater length of optical path are considered. It is evident that more intense spectra would be secured by using the regular one-prism instrument rather than the half-prism, making the camera the same length as collimator. The further advantage of narrower lines for the same slit-width would be obtained by increasing the length of collimator, camera remaining the same. The advantages of the half-prism instrument are its much simpler and more compact and self-contained mechanical form, avoiding some of the flexure and temperature difficulties occurring with the extended one-prism spectrograph.

In conclusion, it may be said that, although the spectra obtained from the grating are disappointingly weak and show that the proportion of the incident light diffracted into the spectrum used is certainly not greater than that estimated by Anderson and does not nearly approach that considered possible, yet even under this handicap it can be used to advantage when the K line is required and if spectra of uniform dispersion are needed. It would also be useful in the red end where prismatic spectra are so unduly compressed. If a grating giving twice the intensity could be obtained, it would be superior even to single-prism dispersion for most work.

The relative flexure of prism and grating spectrograph should also be considered. It is well known that a small change in the position of a prism when at minimum deviation does not displace the spectrum, while the angular movement of a diffracted pencil will be twice that of the grating. Tests of the single-prism spectrograph showed very small flexures of the

order of 2 or 3 km. per second. A similar test of the half-prism spectrograph showed maximum flexure of about 7 km. and of the grating spectrograph of about 20 km. per second. In most exposures the displacement caused by the change of position in hour-angle will not much exceed one-tenth of these amounts, and it is evident that, with proper distribution of the comparison exposures, there should be no appreciable effect on the velocity measures. Hence the question of flexure need introduce no serious difficulties in the use of a grating spectrograph.

II. EXPERIMENTS ON LENGTH OF SPECTRUM WITH OBJECTIVE PRISMS.

While the grating spectrograph was under construction and while waiting for it to be mounted on the telescope, it seemed to be worth while to try some experiments on the length of spectrum method of obtaining radial velocities with an objective prism. The possibility of determining velocities in this way was first pointed out by Pickering and later independently proposed by Orbinsky and Frost, but so far as known no actual determinations of stellar radial velocities have ever been made by this method.

If we consider the spectrum of a star which is at rest relatively to the spectrograph, the star lines will be in their normal positions. If the star is approaching, all the lines are shifted towards the violet and if receding, towards the red. In prismatic spectra, however, the dispersion in the red is only a small fraction of that in the violet, between $\lambda 6563$, H_α, and $\lambda 3934$, K, the ratio is less than one to six while the shift in the lines, the displacement due to velocity, is almost exactly one-fourth at H_α to that at K. Consequently the spectra of stars approaching us are lengthened and of those receding shortened between H_α and K by three-fourths of the velocity displacement at K, and other things being equal the accuracy of measures of velocity should be three-fourths that obtained by a slit spectrograph of equal dispersion.

But there are many other considerations in the measurement of objective prism spectra. It is generally admitted that the lines are not so well defined and that temperature and flexure conditions, not nearly so easily handled with objective prisms, must be looked after at least equally as carefully in objective prism as in slit spectrographs. Moreover the determinations of the velocity displacements of star lines with slit spectrographs depend upon linear measurements of the position of the star line with respect to closely adjacent comparison lines, whereas in length of spectrum determinations only measurements over a long range of spectrum give appreciable differences, and it is evident what effect any change of temperature, especially, would have on this length.

Nevertheless it was thought desirable to try some experiments along this line, particularly as all the apparatus needed was available. Two eight-inch aperture objective prisms of about 15° and 25° refracting angles had recently been received from the J. A. Brashear Company for use with the remounted photographic telescope. A 4½-inch Cooke Telescope with a Photo-Visual Objective had been in the possession of the Astronomical Branch for about 20 years and as the 8-inch stellar camera had been detached from the tube of the 15-inch equatorial it was comparatively easy to attach the tube of the Cooke Telescope, at the proper angle, with the objective prisms in front, in place of the camera.

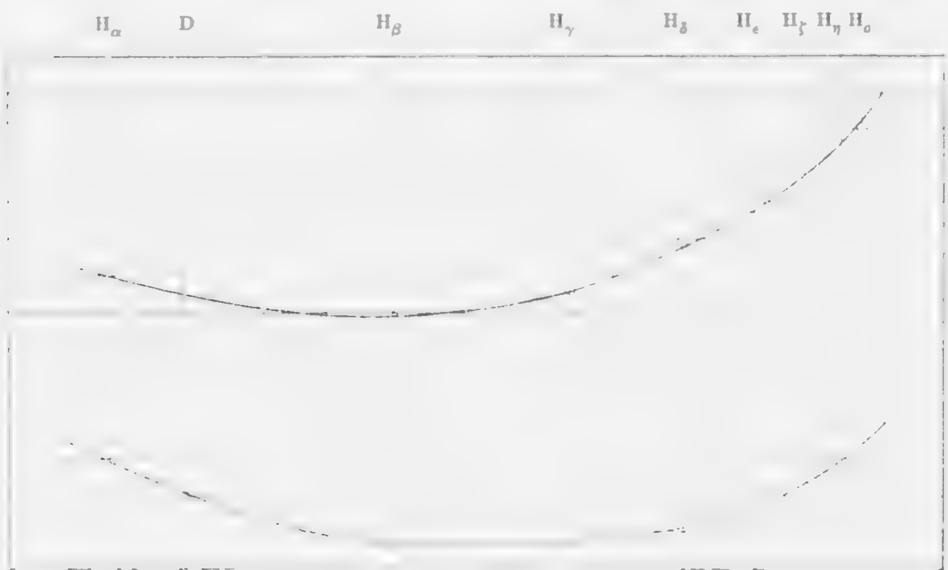
In order to determine the constants of the prisms, the deviations for different wave-lengths, Hβ at minimum deviation, were measured for each prism by a spectrometer with the following results.

DEVIATION AND DISPERSION OF OBJECTIVE PRISMS.

25° Prism.				15° Prism			
Wave-Length.	Deviation.		Dispersion D to	Wave-Length.	Deviation.		Dispersion D to
	°	'	'		°	'	'
5893 D	15	0	0	5893 D	8	47·5	0
4737	15	11·5	11·5	4737	8	57·5	10
4216	15	31	31	4216	9	6	18·5
3934 K	15	41·5	41·5	3934 K	9	12·5	25

The focal length of the Photo-Visual Objective is 81·8 inches hence this makes the length of the spectrum for the 15° prism, from D to K 15·13 and for the 25° prism 25·11 mm., a total length with both prisms of 40·24 mm. The distance between D and K with the one-prism spectrograph is 41·5 mm., consequently they have practically the same dispersion

The colour curve of the objective was determined by Hartmann's extra-focal method by placing a diaphragm over the objective with two slits about half-inch by inch near the edges, the long edge of the slits perpendicular to the line joining their centres, and this latter parallel to the refracting edge of the prisms. Photographs of the spectrum of a bright star, with the plate some 10 mm. inside and outside focus, enabled the various points on the curve to be determined fairly accurately. A plat of



Colour curve of Cooke Photo-Visual—Upper curve.
Curve of Spectral Focus, inclined Plate—Lower curve.
Horizontal lines are one millimetre apart.

the curve is given in the upper curve of the accompanying figure. The minimum focus is about H_β while D and H_γ are each about 0·7 mm. beyond it. H_δ is only about a millimetre beyond the minimum but H_ϵ is 2 mm. and K about 2·5 mm. beyond it. Although well achromatized

visually and remarkably free from a secondary spectrum, it is not so well corrected photographically though of course much superior to the ordinary visual objective, where the distance between the minimum and K is about 3 times that of the Photo-Visual.

For the work to be accomplished in these experiments, it would be preferable if the minimum were shifted towards the violet so that the light at D and H_ϵ, say, would be at the same focus. This would give a longer range of spectrum over which to measure differences of length, a greater quantity of observational data and presumably greater accuracy. This shift can be effected practically when a spectrum is to be photographed by suitably inclining the plate and the dotted line shows a favourable position, an inclination to the perpendicular or original position of about 3°.5. When the colour curve was redetermined for the new position of the plate, it took the form of the lower curve identical of course with the upper except for the change of the slope. It will be seen that the minimum focus is now at about λ4600, that H_β and H_γ are about 0·2 mm., H_ϵ about 0·6, D and H_ϵ about 1·4 and K about 1·7 mm. beyond the minimum. By accommodation, it is evident that practically the whole spectrum would be in good focus when the angular aperture is 1:18. But it is evident that the length of the star spectrum will change much more rapidly for slight departures from the axis than when the plate is normal, and consequently this method was not used.

It is evident that the length of the spectrum produced will be some function of its position-angle with respect to the refracting edge of the prisms and its angular distance from the optical axis, and although it is possible to calculate the changes in length involved, the uncertainties are such that little confidence would be felt in the results obtained. Consequently only one measurable spectrum can be made at a time and one great advantage of the objective prism is lost. Furthermore, as the length of this spectrum will depend upon the temperature and focus, it is necessary to make beside it, preferably by shifting the plate sidewise slightly so that both spectra may be along the axis, a spectrum of a star of known velocity

to act as a standard. It is even more essential than with the slit spectrograph that the temperature of the optical parts should be constant throughout, and as shifting from one star to another introduces a change of position, it is desirable that flexure should be made as small as possible even though the change in length produced by this cause will be small compared to the displacement of the spectrum as a whole.

It was not feasible at this time to enclose the apparatus within a constant temperature case, which would have required a piece of plane parallel glass and an elaborate heating arrangement, nor was it possible with the simple form of mounting to make the flexure very small. But with bright stars and short exposures the temperature changes would be small, and the effect of the change was diminished in some of the exposures by making an exposure on the comparison star both before and after the exposure on the star whose velocity was desired. All three spectra were measured under the assumption that any change would be fairly uniform over the short time required, so that the error due to difference of temperature would at least be much reduced.

Spectra with the two prisms in front of the 4½-inch Cooke Photo-Visual were made of many of the brighter stars, not only to test the exposure time required, but to compare them with spectra of only slightly greater dispersion made by the one-prism spectrograph for sharpness and power of recording detail. Spectra of α Lyrae and α Cygni with both instruments are reproduced in Plate II, and it will be noticed that the slit spectra have much sharper definition. The objective prism spectra are made on Wratten and Wainwright's Panchromatic plate, the slit spectra on Seed 23 whose speed is approximately two thirds the Panchromatic. Exposures on each corresponding pair were simultaneous, the guiding being done on the slit of the spectrograph, the star image trailing across several times. The seeing was only fair and that would account for part of the loss of definition.

So far as relative exposure time is concerned a careful estimate, taking account of speed of plates, width of spectra, and relative intensity for several pairs of spectra show on the average that at H_γ the objective prism spectra require 3·2 times the exposure of the slit spectra. The apertures are 4½ and 15 inches, transmitting amounts of light in the ratio of approximately 1 to 11. This would indicate that the loss at the 0·051 mm. slit, assuming the remaining losses in the two optical systems to be the same, is about 68%, considerably less than usually estimated but greater than obtained in my previous experiments.[1] However, if other parts of the spectrum are compared we find that the objective prism spectra require about 0·7 times at K. 2·0 times at H_δ and 6 times at λ4600. This indicates the strong absorption of the optical train of the slit spectrograph at the violet. If we consider wave-length λ4600, where the absorptions of the optical systems are not very different, we get a loss at the slit of only 45% which agrees very closely with the former experimentally determined loss for a 0·051 mm. slit.[2]

Three pairs of spectra of α Tauri and α Orionis, the last having two exposures of α Tauri and one of α Orionis to minimize temperature errors, were carefully measured and gave the differences in length in revolutions of a half millimetre screw given in columns 5, 7, 9 of the table below.

The difference in velocity of the two stars is obtained from the difference in length of the spectra by dividing by certain constants. These constants were obtained by subtraction of the displacements per kilometre at the different wave lengths, and these latter were derived in the well known way from the constants of Hartmann's formula for the spectra used. The necessary values are given in the table.

1 Report Chief Astronomer, 1908, p. 81. Astrophysical Journal 27, p. 150

2 It must not be forgotten that the proportion of star light occulted at the slit is a function of the seeing and of the quality and focal length of the objective, and these figures are only valid for the 15-inch at Ottawa under average conditions

Lower W. L.		Upper W. L.		Oct. 16		Nov. 9		Jan. 22	
W. L.	Displmt. per km.	W. L.	Displmt. per km.	Diff.	Vel.	Diff.	Vel.	Diff.	Vel.
D	·000388	4400	·000818					·0187	43·5
D	·000388	H_γ	·000864	·0140	31·5	·0320	67·2	·0195	41·0
D	·000388	H_δ	·001038	·0253	38·9	·0410	63·0		
D	·000388	4050	·001090					·0327	46·6
H_β	·000624	H_γ	·000861			·0110	45·8		
H_β	·000624	H_δ	·001038	·0165	39·9	·0200	48·[illegible]		
4400	·000818	4050	·001090					·0140	51·4
		Means			36·8		56·1		45·6

From Bottlinger's orbit of α Orionis[1], the velocity at the end of 1912 would be about $+20$ km. per second and Campbell gives the velocity of α Tauri[2] as $+55{\cdot}1$ km. per second. Applying the annual corrections we obtain the differences in the velocity of α Tauri and α Orionis as 38·9 km. on October 16, 42·9 km. on November 9, and 42·7 km. on January 22, 1913, giving residuals, O–C, of $+2{\cdot}1$, $-13{\cdot}2$ and $-2{\cdot}9$.

The agreement is in the first and last better than I expected from the quality of the spectra and the possible source of error, especially that due to change of temperature, which is very likely the cause of the high residual of November 9.

The two principal difficulties in the accurate determination of radial velocities by this method are in my opinion the poor definition of the objective prism spectra and the maintenance of constant temperature. The latter of course can be overcome by a suitable temperature case with a sensitive thermostat and a fan for circulating the heated air. The poor definition will of course be improved when the optical parts are kept at constant temperature and necessarily then at constant focal length. A further improvement in the definition would undoubtedly be effected if the focal length was decreased, the dispersion being maintained by using more

[1] A. N. 4107
[2] L. O. B.

prisms, or prisms of greater angle. The avoidance of flexure would be a further aid: these with good seeing and careful guiding should enable spectra to be obtained as sharp as those made with a slit spectrograph.

Even if they were as sharp however, the method of measurement necessarily renders the accuracy attainable considerably less than that possible with spectra on which a comparison spectrum has been impressed. Difficulties, and these were felt with stars so nearly similar as α Tauri and α Orionis, will certainly arise unless the star whose velocity is required and the standard or comparison star whose velocity must be known, are quite similar in type.

In conclusion, while these experiments show that radial velocities can be determined by this method with an accuracy likely considerably greater than that possible by the use of an absorbing solution of neodymnium chloride, yet the saving in time over a slit spectrograph when everything is considered is not very great, and certainly I do not think that as accurate measurements can be made. Furthermore the expense and difficulty of obtaining large homogeneous objective prisms will necessarily limit the aperture that can be employed and, consequently, the magnitudes of the stars attainable to those easily within the reach of present equipments.

May I be allowed to suggest a direction for future experiments along this line which anyone possessing a large, angular aperture, apochromatic objective or a parabolic mirror and a slit spectrograph may undertake. If the slit is placed accurately in the focus of the objective, and then opened widely, you have practically the equivalent, so far as light efficiency is concerned, of objective prisms of the full aperture of the objective and giving the same dispersion as the spectrograph. It will of course be necessary to have some means of guiding, such as by reflection from the first prism surface, or by an auxiliary guiding telescope, but one could use as large an objective as desired without getting into difficulties in regard to absorption or lack of homogeneity in the prisms.

III. NEW OPTICAL PARTS FOR THE ONE-PRISM SPECTROGRAPH

It has long been the opinion of the writer that the dense silicate flint glass, the O 102 glass of the Jena Glass Works, which has been almost exclusively employed as the prism material in modern stellar spectrographs, is not the most suitable glass for the purpose, that it is too dense, too highly coloured, and hence too absorbing especially in the violet, to give the best results. This opinion was confirmed by the experiments previously described with the objective prisms of light flint glass. The spectra obtained extended much further into the violet and were much more uniform in intensity along the measurable region than those given by the prisms of O 102 glass.

I, in common apparently with many other spectroscopists, seem to have chosen the O 102 because it was generally used for the purpose and hence presumably the best, without carefully going into the matter of its relative merits as compared with other glasses. It is probably the most suitable among the dense flints, and the high dispersion and resolving power demanded in the modern three-prism spectrograph, together with great compactness and symmetry in form, seemed most easily satisfied by the use of dense flint glass. But that the conditions required in one-prism instruments were not the same was not at first recognized. Their principal usefulness has proved to consist in obtaining the spectra of early type stars where the lines are few in number, are each due to one element only and not blends as frequently occurs in solar type stars, and are very often broad and diffuse. Under these conditions high dispersion and high resolving power are not necessary and indeed are, when the lines are diffuse, a disadvantage. Furthermore, in order to obtain as much material for measurement (as many lines) as possible in spectra which generally have few lines, it is very desirable that a long range of wave-length be photographed at one exposure. When these considerations are taken into account, O 102 glass does not seem the most suitable not only because it is highly dispersive, but chiefly as it is also highly absorbing in the violet thus considerably limiting the range of wave-lengths available.

A search into the literature on the subject revealed little experimental data on the relative absorption of different glasses in the photographic region. The only investigation bearing on this question seemed to be the work undertaken at Potsdam by Vogel, Müller and Wilsing[1] in their investigation of the materials proposed for the 80 cm. objective and the spectrograph to be used with it. Their results are given in the table below for the photographic region but as they only include the Ordinary Silicate Crown O 203, the Ordinary Light Flint O 340, and the Heavy Silicate Flint O 102, the number of materials is not large enough. However, knowing the absorptions of these glasses, we can obtain approximate ideas of the absorptions of other glasses by a comparison of their dispersions in different parts of the spectrum. A rule for this is given in Hovestadt's book[2]. "In comparing two glasses if one of them has the greater total dispersion and at the same time a relatively large dispersion in the upper (violet) portion of its spectrum, especially if accompanied by relatively small dispersion in the lower (red) portion, then this glass has stronger absorption in the ultra violet than the other," and vice versa.

In the table n is the index of refraction for D, Δ is the mean dispersion from C to F and α β γ the ratios of the dispersions between A′ and D, between D and F and between F and G′ to the mean dispersion Δ. The last five columns give the transmission determined experimentally for a thickness of 10 cm. of the glass, for five wave-lengths in the violet.

TABLE I

TABLE OF CONSTANTS—SELECTED REPRESENTATIVE GLASSES

Kind of Glass	Trade No.	n	Δ	Ratios of Dispersion.			Transmission through 10 cm. for Wave-Length				
				α	β	γ	4341	4000	3950	3900	3750
Ordinary Sil. Cr.	O 203	1·5175	·00877	·642	·702	·568	·667	·695		·583	·583
Baryta Light Fl.	O 722	1·5797	1087	·632	·707	·577					
Baryta Light Fl.	O 1266	1·6042	1381	·616	·711	·594					
Ordinary Light Fl.	O 340	1·5774	1396	·614	·713	·600	·569	·614		·456	·388
Baryta Fl.	O 748	1·6235	1599	·605	·713	·604					
Ordinary Silicate Fl.	O 93	1·6245	1743	·604	·715	·609					
Heavy Silicate Fl.	O 102	1·6489	1919	·600	·714	·615	·502	·463	·167	·025	

1 Berichte der Berliner Akademie, Nov. 1896.
2 Jena Glass and its Scientific and Industrial Applications, p. 53, by Dr. H. Hovestadt. Translated by the Everetts: MacMillan

The quantities transmitted through 10 cm. of O 102 glass show how unsuitable it is for prism material, not only on account of its strong special absorption around K, but also on account of the general absorption all along the photographic spectrum. Even if account is taken of the increased thickness necessary with the lighter glasses to get the same resolving power they will still have considerable advantage from λ4000 towards the red, while towards and in the ultra violet the advantage will be very marked. The Ordinary Light Flint O 340 is a considerable improvement over the O 102 especially in the violet and ultra violet, but the Ordinary Silicate Crown O 203 is still better. However, the dispersion of this glass is so low that it was not deemed advisable to use it. On looking over the lists of Jena glasses, the baryta flints appeared the most promising and accordingly three of this type O 722, O 1266 and O 748 are tabulated for comparison above. If we compare O 1266 with O 340 we see that, according to the rule γ less and α greater, it should be considerably less absorbing in the violet, while a comparison of O 722 with O 203 and also with O 1266 shows that the O 722 will be less absorbing in the violet than the O 1266 and only little if any more absorbing than the crown glass.

Consequently a prism of fine annealed glass of baryta light flint O 722 was ordered from the J. A. Brashear Co. In order that it could be placed in the one-prism spectrograph without alterations of the frame it was necessary to have the deviation of the ray at minimum 60°. As it was proposed to carry the measurements further to the violet, the central wave length was chosen as λ4200. This is about midway linearly between λ4550 and λ3934 the usual limits of measurement proposed, or between λ4862 and λ3750 the extreme limits to which the measurable spectrum extends.

The constants of the material of which the prism is made are $n = 1 \cdot 5782$, $\Delta = \cdot 01078$, $\alpha = \cdot 637$, $\beta = \cdot 708$, $\gamma = \cdot 576$, which are even more favourable for transparency in the ultra violet than the tabular constants. Computing in the well known way the refracting angle and dimensions of a prism of this material of 51 mm. (2 inches) clear aperture and with λ4200 at minimum deviation we obtain the angle 68°57′, the length of the sides 118 mm. (4·64

inches) and of the base 133 mm. (5·25 inches). The most favourable angle to make the loss by reflection a minimum for this material is about 64°15′, but the increased loss by the somewhat greater angle is insignificant. The prism was made 57 mm. (2¼ inches) high and consequently is a large block of glass. It is beautifully colourless and transparent and notwithstanding its large size shows no trace of imperfect homogeneity. Careful tests by diaphragming different sections have shown that every part of it defines equally well and as a dispersing piece it is practically perfect.

In order to obtain the full advantage of the transparency of this glass, the isokumatic collimator objective of the spectrograph, whose central component is decidedly yellowish, was replaced by a Brashear Triplet and a Triplet Camera Objective of slightly longer focal length than the Single Material was also obtained. Both of these objectives were cemented with watch oil, which I had learned in Europe had been successfully used for the purpose. No strain can be induced by it in the lenses, it does not evaporate, and the loss by reflection from the internal surfaces is much diminished. However it was found, at the temperatures which a stellar spectrograph reaches in the winter, frequently much below freezing, that the oil crystallizes and can not be used. The oil was replaced by glycerine, which is supposed to remain unchanged at low temperatures, but even this seemed to undergo, at any rate in the thin layers present between the components, some sort of molecular change and appeared mottled and had also to be removed. As will be seen later the loss by reflection in the internal surfaces is rather a serious matter and consequently it was decided to cement the lenses with balsam. Some balsam prepared by Sanger Shepherd and used by the writer in cementing together three-color transparencies was used for the purpose. This had been found not to become hard like the ordinary balsam and consequently is not so likely to introduce strain. The cementing was successfully accomplished and up to the present no ill effects on the definition has appeared.

The spectrograph box was dismounted and the new prism and objectives installed and carefully tested with artificial sources before being tried on the

stars. The definition given was excellent and some preliminary comparative tests of the two prisms showed striking advantages in efficiency, especially in the violet, of the light flint. A curious change in the character of the field given by the triplet was noticed with the two prisms, for, while with the dense flint the field was concave to the lens, with the light flint, it was convex and of smaller curvature. Probably with a prism of intermediate dispersion the field would be flat. The difference in focal length of the centre λ4200 and of λ4550 on one side and K on the other is about 0·1 mm. and, by accommodating, the focus of any part of the spectrum need not be more than 0·05 mm. from the plate. This is not of course so flat a field as that given by the Single Material, but, as the one used with the O 102 prism would not come to focus with the larger prism without changing the camera end, and as it is not possible to quite free this type (when it has such a large angular aperture, about *f8*, as this) from spherical aberration it was thought preferable to use the triplet.

The dispersion given by the combination is 54·5 Å per millimetre at Hγ, 48·3 Å per millimetre at λ4200, the central ray, and 37·5 A per millimetre at K. This is almost exactly three-fifths the dispersion of the spectrograph with the O 102 prism. The linear dispersion can of course be brought to equality by increasing the focal length of the camera, but this is not feasible with the present instrument. The smaller dispersion will presumably give a higher probable error of the radial velocity measurements and the spectra will, perhaps, not show some of the faint metallic lines visible with the denser prism. But the exposure would, other things being equal, be only three-fifths as great and this will be further diminished by the decreased loss by absorption and reflection so that, as will be seen later, less than two-fifths the exposure will be required for the same intensity around Hγ and only about one-ninth at K. This means that a magnitude fainter may be reached and, as the stars within reach of the present equipment are practically all worked up, this will offset some disadvantages.

Before giving the results of the comparative tests of exposures, it may be as well to give briefly the values reached by computation. The losses

by reflection are obtained from the formulae given in any treatise on optics, those used being obtained from Scheiner's Astronomical Spectroscopy. The losses by absorption have been computed in the well known way from the measured values of O 102 glass and from values inferred for O 722 glass from the measured absorptions of O 203 and O 340 and from the run of the dispersions. These values are probably approximately correct. Let us consider first the losses by reflection in the original instrument.

1. Isokumatic Collimator—3 cemented components, 2 free surfaces, incidence nearly normal; transmission at each free surface ·9535, at each cemented surface ·99, after emergence ·8735.

2. O 102 Prism. Transmission at first surface ·874. After two reflections ·779.

3. Single Material Camera 2 separated lenses, 4 free surfaces; transmission at each surface ·9535, after 4 reflections ·8247.

Total Intensity after losses by reflection equals product of 1, 2 and 3 or ·5607.

Losses by reflection in new optical parts.—

1. Triplet Collimator, 3 cemented components, 2 free surfaces. Transmission at each surface ·9535. Transmission at each cemented surface ·99. After emergence ·8735.

2. O 722 Prism. Transmission at each surface ·868. After two reflections ·768.

3. Triplet Camera, 3 cemented components, same as collimator ·8735.

Total Intensity after losses by reflection equals products of 1, 2 and 3 or ·5861.

Losses by absorption.—The mean free path through the prisms was taken as half the length of the base, being 57 mm. in the O 102 and 66 mm. in the O 722 prism. The length of path through the Triplet

collimator and camera lenses was taken as 20 mm., through the Single Material as 10 mm., while the absorptions were assumed the same as that of O 722 glass.

The absorption of the isokumatic collimator was determined, as no data were obtainable for the yellow borosilicate flint central component, by comparing the colour of the complete lens with that of the O 102 prism. It was estimated that about the same depth of colour as the collimator was obtained through between 50 and 60 mm. of the prism glass and consequently the absorption of this objective was taken as equal to that of the O 102 prism. This is probably not exact but sufficiently good for the present purpose. In the following table are given for eight wave-lengths in the photographic region first of all, the measured transmission of 100 mm. of O 102 and O 203 glass, and then values of O 722 estimated from the run of the dispersions. Below these are given the computed transmissions of the various optical parts in the two spectrographs.

TABLE II

TABLES OF INTENSITIES AFTER ABSORPTION THROUGH GLASSES

Material.	H_β	4600	H_γ	4200	H_δ	4000	K	H_ϵ
100 mm. O 102	·740	·620	·530	·480	·480	·460	·200	·020
100 mm. O 203	·865	·825	·725	·680	·680	·690	·620	·580
100 mm. O 722	·875	·825	·725	·670	·670	·680	·600	·540
57 mm. O 102 Old Prism	·842	·761	·696	·658	·658	·639	·400	·108
66 mm. O 722 New Prism	·916	·881	·809	·775	·775	·783	·714	·666
Triplet Collimator and Camera	·973	·962	·938	·925	·925	·925	·903	·884
Single Material Camera	·983	·974	·960	·945	·945	·945	·925	·900
Isokumatic Collimator	·842	·761	·696	·658	·658	·639	·400	·108

The intensities of the emergent pencils from the original and the new optical systems are obtained, of course, by multiplying together the resulting intensities after each loss by reflection and absorption in the components of each system, and are contained in the following table.

TABLE III

COMPUTED EMERGENT INTENSITIES OF LIGHT

Instrument.	H_β	4600	H_γ	4200	H_δ	4000	K	H_ζ
Original System	·391	·316	·260	·229	·229	·216	·0835	·0059
New System	·508	·477	·417	·389	·389	·393	· 341	· 305

This table shows that the new optical system transmits a considerably larger perceniage of the incident light than the old, giving an emergent pencil about 50% stronger in the blue, 75% stronger at H_δ and four times as strong at the K line. Incidentally it also shows how large a percentage of the light is lost in the optical system of even the most efficient form of spectrograph, and how important it is to watch even apparently minor details. For example, cementing the triplet collimator or camera makes the difference between transmission of ·8735 and ·7515 a gain of 16%, while cementing both gives an increased transmission of 35%. Similarly the loss by absorption in the isokumatic collimator is some 30% greater than in the triplet as given in the table above, and this estimated loss is fully borne out by the experimental results.

Experimental tests of the relative efficiencies of the new and old optical systems have been carried out in two ways. First by comparing a number of plates of the same stars, making allowance for the differences in seeing, by the two systems; second by making direct comparative tests directly following one another on the sun and stars in exactly the same way as was performed with the grating spectrograph. The latter method of course gives results probably more reliable and certainly more directly comparable than the former.

The manner of comparing intensities by the first method was to make with the new optical system three spectra with exposures in the ratio of 1, 2, 3 on one plate of one star and repeat this for a number of stars. About ten plates of each of the same stars with the original spectrograph

were then compared with these, and it was comparatively easy to estimate reliably the relative exposure times required to give the same intensity of spectrum at the different wave-lengths.

By the second method, seven or eight exposures on one plate were made with each form of the instrument on the same star. For example, on γ Geminorum, mag. 2·3, exposures of $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$, 2, 3, $4\frac{1}{2}$ minutes were made side by side on a plate with the O 722 prism and the triplet collimator and camera objectives in the spectrograph. Exposures of 1, $1\frac{1}{2}$, 2, 3, 4, 6, 9 minutes directly following on the same star with the O 102 prism and triplet objectives were made on another plate and these last exposures were repeated with the triplet collimator replaced by the isokumatic. All three plates were developed together for the same time. This procedure was repeated in the reverse order for α Leonis and similar exposures were made on the daylight sky. It is evident that numerous accurate comparisons of the relative intensity at any wave-length can easily be made from such a series of exposures.

The following table contains a summary of the mean values obtained by both methods.

TABLE IV.

MEAN VALUES OF RELATIVE EXPOSURES AT EIGHT WAVE-LENGTHS

Method.	No.	Optical Systems Compared. Exposure of last unity.	H_β	4600	H_γ	4200	H_δ	4000	K	H_ζ
First	1	O 722 Triplet O 102 Isokum	·381	·402	·363	·285	·225	·156	·108	·059
Second	2	O 722 Triplet O 102 Triplet	·570	·554	·471	·395	·313	·263	·177	·123
"	3	O 102 Triplet O 102 Isokum	·785	·754	·726	·712	·712	·687	·638	·586
"	4	O 722 Triplet O 102 Isokum	·508	·501	·406	·351	·270	·180	·115	·080
"	5	Product of (2) and (3)	·447	·418	·342	·281	·223	·181	·113	·072
"	6	Mean of (1), (4) and (5)	·445	·440	·370	·306	·239	·172	·112	·070

In (6) of the preceding table we get the relative exposures experimentally determined for the new and old optical systems, and it will be seen how marked a saving in exposure time is effected. The new system requires less than two-fifths the exposure time of the old at H_γ, one-quarter at H_δ and only one-ninth at K. It must not be forgotten however that the dispersion of the new system is only three-fifths that of the old, and to make them directly comparable the figures in (6) should be multiplied by five-thirds.

This has been done in the following table, where is also given the ratio of the computed intensities of the emergent light from the two systems obtained by dividing the emergent intensities in Table III.

TABLE V

RELATIVE COMPUTED AND EXPERIMENTALLY DETERMINED EFFICIENCIES

	H_β	4600	H_γ	4200	H_δ	4000	K	H_ζ
Experimental Old : New.............	·742	·733	·617	·510	·398	·287	·187	·117
Computed Old : New...............	·770	·666	·624	·589	·589	·550	·245	·019

There is good agreement in general in these figures, and the deviation between λ4200 and λ4000 is probably mostly due to insufficient data as to the absorptions of the glasses in this region. I am convinced that the experimental values are nearly correct, and that the run of the absorptions in the O 102 glass must be much more gradual in its progression from H_γ to K than is given in the tables. Such a progressive run of the absorptions would make excellent agreement between computed and experimental values. There is another factor which will influence the magnitude of the experimental values so far as the relative values for different wave-lengths are concerned, and that is the fact that all wave-lengths of the light forming the star image are not in sharp focus on the slit. Owing to the colour curve of objective and correcting lens there is a difference of over three millimetres in the position of the star focus for H_γ light and for that at the ends

of the spectrum H_β and K. The slit was placed so that light at wave-lengths about λ4000 and λ4650 were in focus upon it, and Table V shows evidence of this in the higher experimental value at λ4600.

It may be pointed out that (3) in Table IV gives the relative exposures when triplet and isokumat collimator are interchanged, and that they agree well with the estimated values of the absorption of the isokumat objective in Table II. until we get near K. Here it seems that the absorption of the borosilicate flint of the isokumat differs from that of the O 102 and produces a more gradual change. Both sets of figures form striking evidence of the unsuitability of this objective for spectrographs. In addition to the gain in efficiency another great advantage of the new optical parts is the uniformity in the intensity of the photographed early-type spectrum. With the O 102 prism, in order to obtain sufficient exposure on the K line to make it measurable, the region around H_γ was so much over-exposed as to block up the fainter metallic lines. Furthermore, as can be seen in Plate II, the spectra from the light flint prism contain four or five more measurable hydrogen lines than the others, thus considerably increasing the material available for measurement in stars with few lines.

The results of this investigation may be summarized as follows:—

1. The dense silicate flint, O 102, glass almost universally employed as prism material in stellar spectrographs has been shown to be too highly absorbing all along the photographic spectrum and especially towards and in the ultra-violet for the best results in radial velocity work. This is especially the case in single-prism spectrographs employed on early-type stars.

2. The substitution of a baryta light flint prism O 722 for the O 102 has caused a decrease in the exposure times required to produce the same intensity of spectrum (when both are reduced to the same dispersion) of 22% at H_γ, 48% at H_δ and 70% at K, besides giving considerably more measurable material in the ultra-violet without over-exposure around H_γ.

3. The substitution of a Brashear Triplet for the Isokumat Collimator Objective has, owing to the strong absorption of the latter, effected a further saving of about 30%.

4. The cementing of the contact curves of the triplet collimator and camera objectives diminishes the loss by reflection over what would occur with uncemented lenses by over 30%.

5. The ratios of the intensities of the emergent pencils from the old and new optical parts are 0·62 at H_γ, 0·40 at H_δ, 0·19 at K, and the actual ratios of the exposures required owing to the three-fifths dispersion of the new system are 0·37 at H_γ, 0·24 at H_δ and 0·11 at K. Although the smaller dispersion will likely entail proportionately larger probable errors, the fact that nearly all the material available for the present equipment has been worked over and that the new optical parts enable stars at least a magnitude fainter to be reached, should justify the diminished accuracy.

6. Finally the investigation has shown the importance in stellar spectroscopy, where the light is always meagre in quantity, of so selecting the materials and designing the optical parts of a stellar spectrograph that all the losses by reflection and absorption may be minimized; and the results indicate what a great saving in exposure time and consequent increase in output and range may thus be effected.

DOMINION OBSERVATORY,
OTTAWA,
February 1914

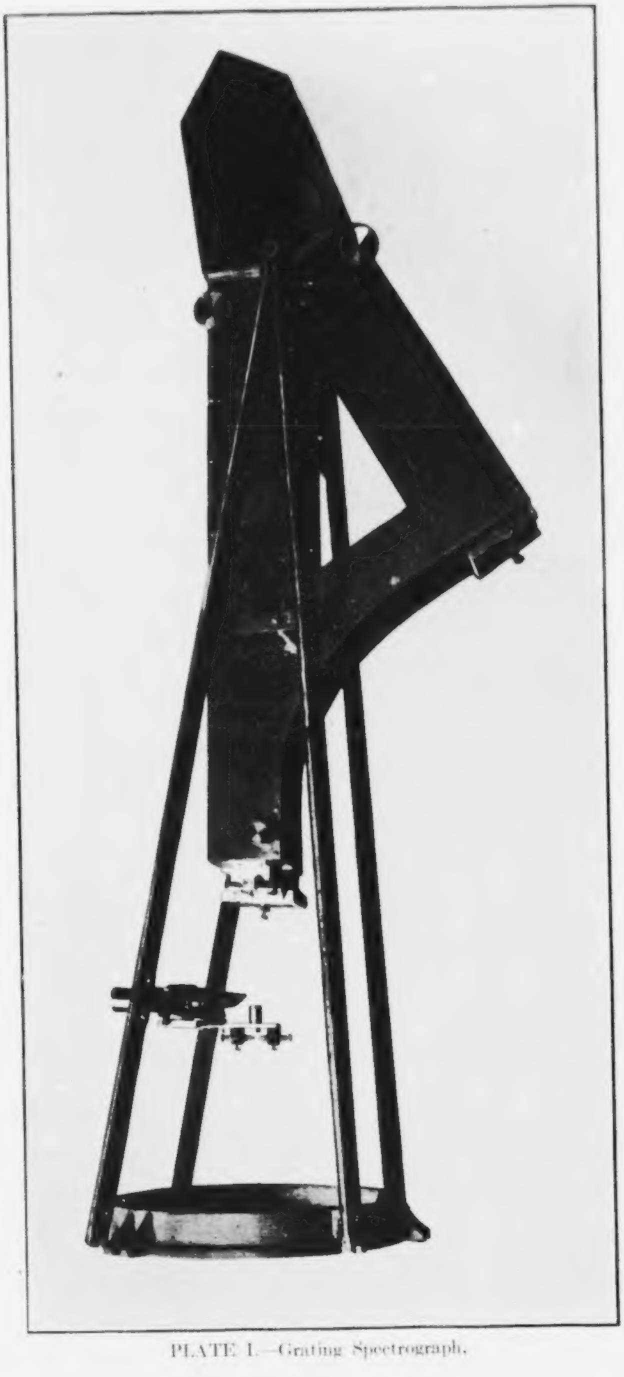


PLATE I.—Grating Spectrograph.

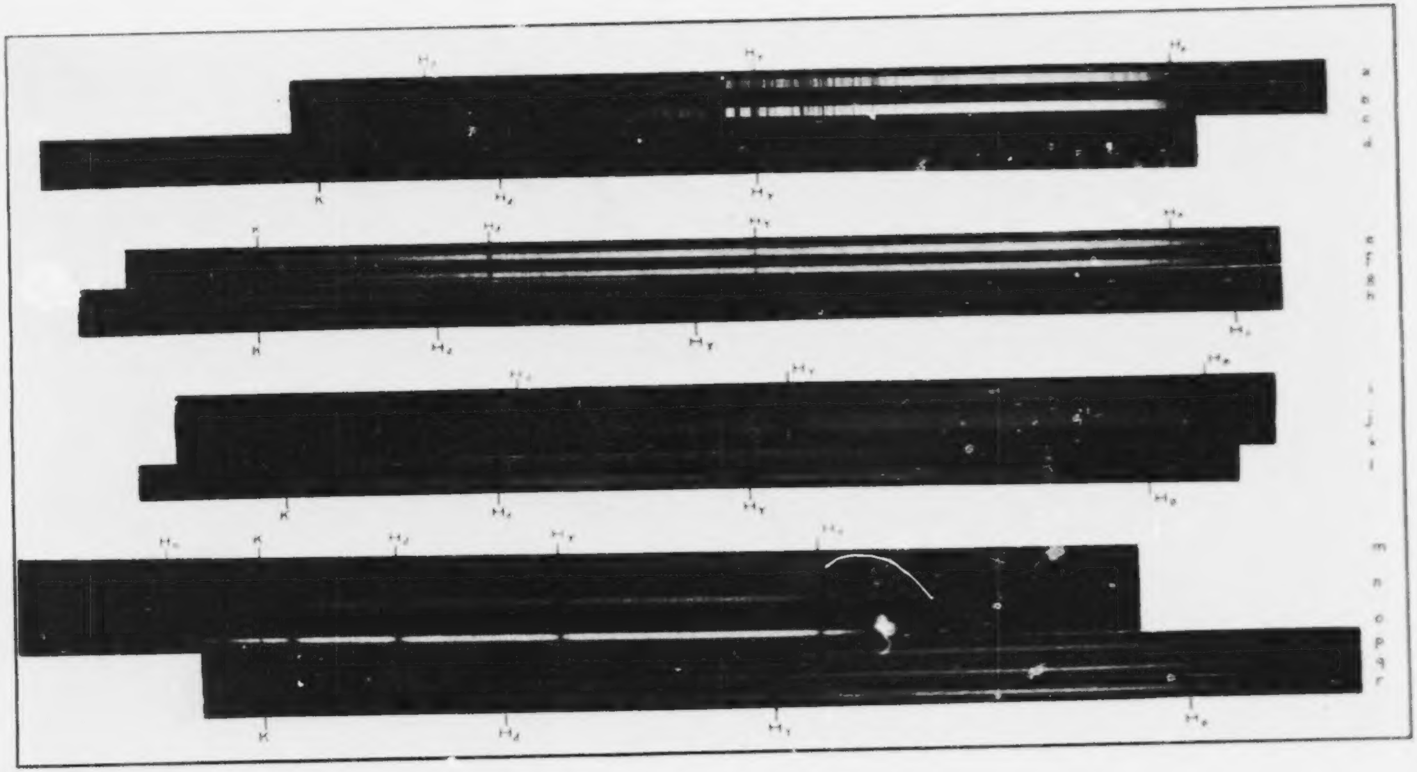


PLATE II.—Examples of Spectra.

a and *b*—III 8 Solar Spectrum: Exposures 2 and 3.
c and *d*—Littrow Grating Solar Spectrum: Exposures 2 and 3.
e and *f*—One Prism: Rigel Spectrum: Exposures 2 and 3.
g and *h*—Grating: Rigel Spectrum: Exposures 2 and 3.
i and *j*—α Cygni, α Lyræ: One Prism, Slit Spectra.
k and *l*—α Cygni, α Lyræ: Objective Prism Spectra.
m, *n*, *o*—γ Geminorum, O 722 Prism: Exposures 1, 2, 7½.
p, *q*, *r*—γ Geminorum, O 102 Prism: Exposures 3, 6, 9.